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Potential Methods for Reducing Shoaling in Harbors and Navigation Channels

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PURPOSE. This Coastal and Hydraulics Engineering Technical Note (CHETN) contains a literature review giving a brief compilation of case studies related to potential methods adopted for reducing sediment deposition in harbors and navigation channels. All over the world there are numerous sites where the bed consists of noncohesive sediment (sand and silt) alone. Examples of important engineering projects in areas consisting of clays alone are probably very few. Invariably, fine sediments occurring in the natural environment consist of a mixture of cohesive and noncohesive sediments. The literature review included in this technical note covers both types of sediments.

In addition to gathering information on projects executed at various sites, this literature review also includes findings of hydraulic and numerical model investigations. These include results of investigations on the effect of construction of new structures, modification of existing structures, or modification of site conditions. Experience gained through these case studies will offer valuable guidance in planning and designing future projects. Note that those options that were investigated in laboratories for research purposes but did not work when adopted for a particular project are included because they might work at other locations.

INTRODUCTION. Harbors and navigation channels are designed mainly based on site conditions and specific requirements. Shoaling or sediment deposition is an unavoidable part of most of the harbors and navigation channels. Data on quantities and cost of annual maintenance dredging in the United States are published on an internet web page by the Navigation Data Center of the US Army Corps of Engineers (2002). Data for the years 1995 through 2000 show that the average annual maintenance dredging in Federal navigation projects was 176 million m^3 (230 million cu yd) at a cost of about $500 million. This represented 86% of the total dredging volume and 75% of the total dredging cost per year for the Corps. In addition, maintenance dredging is also done at non-Federal marinas, docks, basins, and small boat harbors. Keeping the rate of shoaling to a minimum is a major consideration for site selection and harbor design. The obvious reason for the need to reduce shoaling is to reduce recurring cost of dredging. Often shoaling increases later as a result of implementation of harbor expansion schemes or other unforeseen reasons, and it becomes essential to take remedial measures to reduce shoaling after the harbor becomes operational.

It is essential to identify the source of sediment to adopt a suitable method to prevent contribution from that source. In addition to littoral transport, simple deposition of noncohesive sediments, flocculation and quick deposition of cohesive sediments, and transport along the bed or in suspension, the following other causes may also be responsible for sedimentation in harbors and navigation channels:

- Sliding down of soft top layer along the slope of channel bank
- Mud transport originating from adjacent areas
- Slope instability

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- In rare occasions, vessel collision on the bank causing temporary and local bank instability
- Shifting of offshore bar
- Wind-induced sand transport.

Adopting the following methods can reduce the volume of shoaling:

- Cut down sediment inflow from the source.
- Provide barrier to prevent sediment entry.
- Catch the sediment before it enters the sensitive area.
- Divert sediment away from the area of interest.
- Prevent sediment recirculation.
- Prevent sediment deposition.
- Employ other methods.

Note that the ultimate objective of reducing recurring dredging costs may be achieved not only by reducing the volume of shoaling, but also through one or more of the following highly effective methods:

- Reduce the volume of unnecessary dredging (Holiday et al. 1984); adopt navigable depth concept (Herbich et al. 1989).
- Reduce the need for frequent dredging (achieve longer time interval between consecutive dredging operations; install hydraulic jet arrays; carry out advance maintenance dredging).
- Use alternative and more economical dredging equipment (Holiday et al. 1984).
- Select disposal sites from which dredged material will not return to the project areas.
- Adopt new dredging practices (hydraulic versus agitation dredging).
- Adopt new disposal practices (open water versus confined areas).
- Make beneficial uses of dredged material so as to make the project economically feasible.

CASE STUDIES OF SHOALING REDUCTION IN HARBORS AND CHANNELS. It is highly recommended that previous experience of successful projects be taken into account whenever available so as to avoid expensive and sometimes irreversible mistakes in attempts made towards achieving reduction in shoaling.

Dillingham Harbor, AK. Harbor shoaling is a significant problem when coastal waters are laden with suspended solids and the tidal range is high such as in Alaska. Under these circumstances half-tide harbors are often constructed as enclosed basins adjacent to, rather than within, navigable estuaries for use of small crafts. The unique feature of a half-tide harbor is a sill placed in the navigation channel at an elevation higher than the bottom of the harbor basin. When the tidal level is low, the sill retains water in the harbor for vessel floatation.

An enclosed small-craft half-tide harbor at Dillingham, AK, shoaled at a high rate of about 2m/year (6 ft/year) since it was constructed in 1960-1961 (Smith 1984). This enclosed small-craft half-tide harbor has a diurnal tidal range of 5 to 6 m (16 to 20 ft) and the suspended sedi-

ment concentration is on the order of 1,000 mg/L (0.06 lb/cu ft). Diurnal tidal ranges of 5 to 6 m (16 to 20 ft) in Bristol Bay and 6 to 9 m (20 to 30 ft) in Cook Inlet produce tidal currents exceeding 3 m/sec (10 ft/sec). Hence, a large concentration of sediment remains in suspension. The large tidal range precluded a channel and basin that provided access at all stages of tide. Hence, a rock sill was placed in the 15-m- (50-ft-) wide creek channel with a top elevation of +2.1 m (7 ft) mean lower low water (mllw). The basin behind the sill was dredged to +0.6 m (2 ft) mllw, providing 1.5-m (5-ft) depth inside the basin at low tide for floatation of small vessels. This sill elevation allowed navigation access in and out of the harbor approximately 46% of the time.

Agitation dredging is mostly not recommended because the stirred up sediment usually finds its way back to the navigation channel. The suspended sediment may also cause an adverse environmental impact. However, Everts (1976) mentioned that the shoaling pattern and natural conditions at Dillingham might permit this method of dredging during ebb because the sediment would be expected to be flushed out away from the region of interest without causing adverse environmental impact.

Modifications of existing facilities were necessary for harbor expansion to accommodate 300 or more fishing vessels in the Dillingham Harbor. In addition to increasing the area of the existing basin, one option consisted of lowering the entrance sill which would allow more efficient flow of traffic and meet the required objective. However, it would also allow additional volume of silt-laden water in the harbor area resulting in increased maintenance dredging. Hence, the option of lowering the sill was ruled out. Three other options were considered to reduce the volume of siltation.

Removable float system. A float system was installed to serve as small-craft berths, consisting of heavy-duty barge-like steel floats that can endure repeated seasonal removal. These units connect in such a way that a minimum number of pilings are required to hold them in position. A raft of two barges will be sufficient to carry a small crane for placing and removing pilings. The float arrangement was laid out to accommodate the periodic work of the dredge between fingers. Individual slips were not provided due to the transient nature of the Dillingham fleet. This float system would accommodate 100 gillnetters moored singly. Multiple berthing three abreast would accommodate 300 vessels, which meets the project requirement.

Entrance channel closure structure. The most unusual feature planned for the bor was construction of a steel closure structure in the entrance channel. This structure incorporates a 15 m- (50-ft-) wide sill at +1.2 m (+4 ft) with reference to mean lower low water and allows the basin to be closed off from the silty water of the bay during winter months. Closure from October through April was estimated to reduce the annual sedimentation to at least 60% of what would otherwise occur. This reduction was vital in conceiving a plan with annual maintenance dredging requirements less than the permissible maximum quantity of 92,000 m^3 (120,000 cu yd). The structure includes a cathodic protection system and a system of steam thawing pipes for removal of the steel stop logs each spring. The banks adjacent to the offshore side of the structure are to be protected from erosion by a rock revetment.

Hydraulically optimized basin geometry. Several layout plans were evolved for an expanded harbor taking into account the maintenance difficulties and cost benefit considerations for each. Tidal circulation in an expanded basin under various configurations was numerically

simulated for study. The results were inconclusive, except that spur dikes, variable bottom elevations or two entrances showed no distinct advantages. None of the tested configurations maintained velocities sufficient to prevent the settling of 0.006-mm- (0.00024-in.-) size particles present in the tidal water at the site.

Ninilchik Harbor, AK. Ninilchik Harbor is located on lower Cook Inlet, AK. The diurnal tidal range is 6 to 9 m (20 to 30 ft) and tidal currents exceed 3 m/sec (10 ft/sec). The following measures were considered / tried at the site for reducing sedimentation (Smith 1984): (1) A sediment trap was excavated upstream of the basin, (2) French drains were installed to stabilize basin slopes, (3) Smoothing the basin contours was tried, (4) Installation of hydraulic diversion dikes was considered, and (5) Feasibility of a closure structure was investigated. None of these were found to be effective or economical.

Various configurations of breakwater alignment, sill elevation, and basin shape were investigated. It was concluded that maintenance dredging would be much less at a new site on the south side of Cook Inlet because the bank sloughing and the contribution of river sediment directly into the harbor would no longer exist. Unfortunately, the project was abandoned in October 1983 because affordable means to provide necessary armor rock for breakwater construction could not be provided.

Mare Island Naval Shipyard, Vallejo, CA. The following four devices reported by Bailard, Dellaripa, and Flor (1986), have been validated through field tests and have shown great potential in reducing the Navy's maintenance dredging burden at this shipyard located in the San Francisco Bay Area.

Spatial scour jet array. A scour jet array system is found to be effective in reducing wanted sediments. It consists of a series of horizontal, near-bottom water jets which are briefly activated during each ebb tidal cycle. The bed shear stress imposed by the jet discharge resuspends recently deposited sediment, creating a fan-shaped scour pattern in front of each jet. Once suspended, the sediment is carried away from the berthing area by tidal currents during the ebb.

Vortex foil array. A vortex foil array device can be provided for reducing sedimentation at berthing and approach areas exposed to moderate currents. These arrays consist of a series of underwater foils similar in cross-section to airplane wings which are moored about 0.3 m (1 ft) above the bottom by a short tether wire connected to a swivel and screw anchor. Each delta shaped foil is buoyant, with its lifting surface oriented either upward (a downwash foil) or downward (an upwash foil). Tidal currents flowing past the foil cause horseshoe-shaped vortices to be shed from the foil's trailing edge. The vortices are advected downstream by the current, enhancing the bottom shear stress and resuspending newly deposited sediments. In the downwash mode, the full energy of the vortices is directed at the bottom, resuspending loosely consolidated sediment. In the upwash mode, the sediment is directed into the water column and carried out of the berthing area by the tide. Normally combinations of downwash and upwash foils are used.

Barrier curtain. Barrier curtains are found to be effective in reducing sedimentation in semi-enclosed berthing areas with limited flushing. Barrier curtains work on the exclusion principle. Field studies have shown that, under conditions of deposition, 90% of the sediment is car-

ried in the lower 10% of the water column. As a result, a partial height curtain can be used to exclude the sediment-laden bottom water from a berthing area while still allowing normal tidal exchange to occur at the surface. These curtains are pneumatically controlled for raising and lowering to accommodate navigation.

Venting canal concept. The Navy has evaluated this device which was developed by the Scripps Institute of Oceanography for reducing sedimentation in the turning basin at the Naval Station, Mayport, FL. The concept involves constructing a shallow canal connecting the basin with the adjacent St. John's River. The canal would function by preferentially filling the turning basin with relatively sediment-free water entering the existing entrance channel.

Hudson River Channel, NY. The annual maintenance dredging in 1965 in the lower 18 km (11 miles) of the Hudson River was about 1.2 million m^3 (1.6 million cu yd) for the Federally maintained navigation channels and 2.3 million m^3 (3.0 million cu yd) for the privately owned pier slips. Several plans were considered to reduce shoaling in this reach. These consisted of channel realignment, sediment basin, dikes, closure gates, and cross-section enlargement. A comprehensive hydraulic model which correctly reproduced tides, tidal currents, density currents, and shoaling in the entire New York Harbor complex was used to study these plans. Sedimentation basin plans were intended to encourage deposition of shoal material in the basins and thus reduce shoaling of the channels and pier slips. Reduction in maintenance dredging costs is achieved by either: (1) decreasing the frequency of dredging and thereby reducing the unit cost, or (2) concentrating shoaling at more favorable locations from the standpoint of dredged material disposal, which would also reduce unit cost.

The conclusions of the study (Simmons and Bobb 1965) were:

- A dike extending from the New Jersey shore and enclosing shoal Area 6 would not materially reduce shoaling in Area 6 as intended, and would cause significant increases in shoaling elsewhere, particularly in the maintained slips.
- Significant reductions in shoaling rates in existing shoal areas could be effected by realigning or shifting the deep natural channel from the Manhattan side of the Hudson River to the New Jersey side.
- Closure of the Harlem River to ebb flow, combined with enlarging the Hudson River cross section at the George Washington Bridge, would encourage flushing of the Hudson River during ebb flows and thus result in shoaling reduction throughout the problem area. Construction of a control structure was recommended.
- A practical means for reducing annual shoaling rates in pier slips was not found.
- It was recommended that potential benefits of dredging a sediment trap in the upstream end of the 9-m (30-ft) channel should be evaluated. Construction and operation of such a trap will probably not be economical if periodic maintenance of the trap is performed by conventional hopper dredge. However, it is possible that the demand for fill material for land reclamation, which might be obtained from the trap by the pipeline dredge, may eventually make such a scheme economically feasible.

Lower Hudson River, NY. A major item of maintenance, and a deterrent to the full use of the Hudson River frontage for maritime purposes, has been the heavy shoaling which occurs

in the channel and adjacent slips of the lower estuary. Investigations to find a solution to this problem included determination of: (1) the sources of sedimentation, (2) the characteristics of the fresh and saltwater components of flow within the estuary, (3) the quantity of shoaling which occurs, and (4) the fundamental principles affecting the sedimentation process. Because of the non-analytic character of the complex factors involved in this problem, two hydraulic models were used to investigate a number of possible solutions (Duke 1961). Out of several plans and variations tested on the models the following options appeared effective: (1) use of sedimentation basins, (2) realignment of the deepwater channel by fills and dikes, and (3) closure of flow from one of the several component waterways.

Port of Hamburg, Germany. Eddy currents often cause shoaling, and dredging the shoal is not always cost-effective. A new method developed in Germany uses an innovative low training structure called the current deflector wall (CDW) to eliminate the eddy currents. A CDW is a fixed vertical-walled structure with a curved deflector wall that extends through the full depth of the water. A rounded vertical-walled addition to the existing upstream entrance comer will usually be required to complement the CDW. The current deflector structure modifies flow pattern in such a way as to break down or prevent the formation of eddies. This method has been successfully used in 1990 at the Kohlfleet Harbor, Port of Hamburg, Germany. The current deflector wall has eliminated eddy formation, improved navigation, and resulted in about 40% reduction in shoaling.

Alexander (1993) made an engineering evaluation of the current deflector wall as a device for navigation channel maintenance. He has cautioned that while considering CDW as an option, it is important to distinguish eddy-generated problems that make such a structural alternative feasible.

Charleston Harbor, SC. Charleston Harbor, SC, was deepened from 9.1 m (30 ft) to 10.7 m (35 ft) in the 1940s. Also, a large amount of water from the Santee River was diverted to the Cooper River in 1942 as part of a power generation project. This increased the average annual freshwater discharge into Charleston Harbor from 23 m^3/sec (800 cfs) to between 57 and 792 m^3/sec (2,000 and 28,000 cfs) depending on the electrical demand. Shoaling in Charleston Harbor, located on the Cooper River, increased from 84,000 m^3 (110,000 cu yd) per year for the preproject condition to 7.6 million m^3 (10 million cu yd) per year after the Project. The US Army Corps of Engineers (1966) concluded beyond a reasonable doubt that the increased freshwater flow transformed the earlier well-mixed estuary into a partly-mixed type, increasing predominance of flood currents at the bottom. This prevented near-bottom suspended sediment in the river from discharging into the sea, which then deposited within the harbor area.

To restore the preproject conditions of low maintenance dredging, it was necessary to redivert water from the Cooper River back to the Santee River. At the same time, it was necessary to maintain adequate flow in the Cooper River for flushing pollutants and for meeting the health, aesthetic, and recreational requirements. Studies indicated that a flow of 8 m^3/sec (3,000 cfs) would be sufficient to revert Charleston Harbor to a well-mixed type of estuary as before. It was estimated that the rate of maintenance dredging following rediversion will probably be 40 to 75% less than the average during the 16-year period 1966-1982 (Patterson 1983).

Teeter (1989) analyzed field data on various parameters before and after rediversion. He concluded that the harbor conditions were optimum for a river discharge between 85 and 127 m^3/sec (3,000 and 4,500 cfs). This flow range was recommended as the weekly average flow in Cooper

River from Pinopolis Dam. The average annual gross dredging for the Charleston Harbor for the period 1965 through 1984 was 4.7 million m^3 (6.19 million cu yd). The reduction in dredging after rediversion was estimated to be between 70 and 74% depending on the variation in the amount of freshwater flow from 127 and 85 m^3/sec (4,500 to 3,000 cfs), respectively.

Delaware City Channel, DE. The Tidewater Oil Company, Delaware Refinery, at Delaware City, DE, explored the possibility of reducing shoaling at their facility. Six plans were developed consisting of dikes and two locations of sand traps. Bobb (1965) reported results of hydraulic model investigations of these plans. It was concluded that all the plans tested had an adverse effect on total shoaling in the company channels. If the plans are implemented, total shoaling was expected to increase by amounts varying between about 42,000 m^3 (55,000 cu yd) and 363,000 m^3 (475,000 cu yd) per year depending on the plan.

Delaware River Channel. The Marcus Hook-Schuylkill River reach of the Delaware River had sediment shoaling problems. A fixed-bed hydraulic model was used to qualitatively assess the relative merits of several proposals consisting of 17 plans (Bobb 1967). The following conclusions were drawn based on the model studies: (1) A significant reduction in back channel shoaling can be achieved by complete closure of the Tinicum Island back channel, (2) A 76-m-(250-ft-) wide small-boat channel through Tinicum Island will decrease the reduction in shoaling but will improve circulation, and (3) A combination of three sediment traps and a deepened portion of Marcus Hook anchorage would materially reduce navigation channel maintenance from the Philadelphia Navy Yard to Marcus Hook.

Port Orford, OR. A breakwater constructed at Port Orford in 1935 was extended by 168 m (550 ft) in 1961. This altered the current pattern in the harbor adversely by forming an eddy which induced sediment deposition. Soon after breakwater extension, the harbor area adjacent to the pier started shoaling. Chatham (1981) has reported hydraulic wave model studies conducted to rectify the situation. He concluded that neither removing segments of breakwater, nor breakwater realignment, nor lengthening of the existing breakwater along the same alignment, would be beneficial. Instead, an extension of the Fort Point breakwater by 183 m (600 ft) at an angle of south-45-deg-west would prevent shoaling by wave-induced currents from any prevailing direction. This case shows that well-studied structural modifications can be beneficial as remedial measures. Usefulness of hydraulic model investigations in discarding unfavorable options and selection of the correct option is also demonstrated clearly by this case.

Sunny Point, NC. The Military Ocean Terminal, Sunny Point (MOTSU) is located on the Cape Fear River, NC. The facility has experienced significant shoaling in excess of 1.45 million m^3 (1.9 million cu yd) per year since it was constructed in 1953. Faced with a disposal area shortage, and the fact that spring freshets can cause significant shoaling within a few weeks, MOTSU embarked on a shoaling study which included the use of physical and numerical models (Holiday, Wutkowski, and Vallionos 1984).

A reconfiguration of the channels/basin geometry was developed having a constant width and depth, and hydraulic scour jets were proposed to be installed along the wharves to help maintain the berth areas at project depth. The planned improvements were not designed to eliminate or even reduce the shoaling problem at MOTSU. The problem is expected to become manageable by:

- forcing the shoaling to occur with a more uniform distribution, thereby eliminating the large, localized shoals in the berth areas,
- restricting the majority of the shoaling to the seasonal high shoaling period which will extend the time project depths are maintained, and
- maintaining the berths with agitation, which will allow full use of the terminal by ships, which can navigate through the low density shoals during the high shoaling season.

Cattaraugus Creek Harbor, NY. Cattaraugus Creek, located on the south shore of Lake Erie, is approximately 113 km (70 miles) long and flows generally westward, entering the lake about 39 km (24 miles) southwest of Buffalo Harbor, NY. Flooding occurs almost every year along the lower reaches of Cattaraugus Creek when melting snow and spring rains swell the creek. This flooding is partially due to the limited capacity of the existing creek channel, but the major contributing factor is the presence of a restrictive sand and gravel bar at the creek mouth. This bar, formed mainly by littoral drift due to wave action, at times virtually closes the outlet and provides a natural barrier encouraging the formation of ice jams which cause significantly higher stages and damages than those caused by discharge alone.

Navigation difficulties are also experienced at the mouth of the creek due to the shallow depths and the constant shifting of the bar across the entrance. Improvements at the mouth and lower reaches of the creek were needed to rectify the shoaling problems. Studies were conducted (Bottin and Chatham 1975) on a 1:75 undistorted wave model. It was concluded that out of the nine improvement plans tested involving a navigation opening and entrance channel oriented toward the northeast, plans consisting of construction of rubble-mound breakwaters and reduction of the navigation opening between the breakwaters to 91 m (300 ft) provided the best protection with respect to shoaling.

Savannah Harbor, GA. The lower portion of the Savannah River estuary system has two main channels. Although they are basically parallel over most of the reach, they cross downstream of the harbor area. Upstream of the crossing, the two channels are called Front River which has the navigation channel, and Back River. Downstream of the crossing they are called North Channel (navigation channel) and Write River. Various plans to reduce heavy siltation in the harbor area of Front River were examined in a physical model (US Army Engineer Waterways Experiment Station 1963).

The recommended (and eventually constructed) plan consisted of a sediment trap in the lower portion of Back River, and a tide gate structure in Back River upstream of the trap. The gates would be closed during ebb tide, forcing more flow down through Front River. This would flush sediments downstream in the navigation channel. The gates would be opened during flood tide, allowing normal flow up through Back River. This would attract sediments from the navigation channel into the Back River sediment trap. Relocation of the sediment deposition area not only reduced shoaling in the harbor area, but also resulted in dredging operation closer to available disposal areas. Navigation channel shoaling was reduced by about 30%. Other plans considered involved diversion of the fresh water from Savannah River through Back River and Wright River to the ocean, and diversion of the fresh water through Back River and North Channel to the ocean.

Southwest Pass, Mississippi River, LA. Southwest Pass of the Mississippi River is the principal navigation channel between the Gulf of Mexico and New Orleans, LA. During 1965 this was being maintained to provide a navigation channel 11-m (35-ft) deep by 244-m (800-ft) wide from Head of Passes to the end of the jetties, and 11-m (35-ft) deep by 183-m (600-ft) wide in the bar channel downstream thereof. Improvement works to secure and maintain the authorized 12-m- (40-ft-) deep channel with 0.61 m (2 ft) overdredging were subsequently designed on the basis of prototype studies and the results of model investigations presented by Simmons and Rhodes (1965).

During high freshwater discharge, extensive shoaling occurs in the jetty and bar channels of Southwest Pass. Several factors are involved in these shoaling characteristics, such as littoral currents, tidal action, wind and waves, freshwater discharge, and the location of the saltwater wedge as determined by the freshwater discharge. The most important of these factors is the freshwater discharge which, as previously stated, controls the location of the saltwater wedge. Rapid shoaling usually occurs near the tip of the saltwater intrusion in a highly stratified estuary such as Southwest Pass. The heavier particles of sediment (bed load) move along the riverbed under the influence of freshwater until arrested upon encountering the saltwater. Other particles which are transported in suspension in the fresh water gradually settle through the interface when the fresh water loses its velocity in the Gulf, and are retransported upstream by the saltwater currents in the lower layers to the vicinity of the saltwater tip. The channel reach occupied by the upstream limits of the intrusion is therefore a focal point for accumulation of sediment from both upstream and downstream. The heavier particles are deposited just upstream from the intrusion limits, and the lighter particles are deposited just downstream from them.

Studies were conducted in a 1:500 horizontal, 1:100 vertical scale hydraulic model to test various plans for reducing shoaling. It was concluded that plans involving a curved realignment for the jetty channel and plans involving relocating the bar channel would greatly reduce shoaling for a 13-m- (42-ft-) deep channel. Tests also indicated that reducing the channel width throughout the pass from 244 m to 183 m (800 to 600 ft) would also be beneficial.

Columbia River, OR/WA. Numerical model studies have been reported by McAnally (1983) on the examination of the effect of south jetty at the Columbia River mouth along with its modifications in the context of reducing channel shoaling. The seaward portion of the jetty was degraded to elevations below low tide levels. Rehabilitation of the jetty to its original above-water crest elevation was previously authorized. The model study indicated that in its present condition, navigation channel shoaling is less than with the rehabilitated condition. Apparently the degraded seaward portion of the jetty acts as a weir preventing some bottom sediments from entering the entrance channel during flood currents. The submerged portion of the jetty apparently is sufficient to confine ebb currents and flush sediments out into the ocean. Thus, in this specific case, the present length of the jetty was found to be optimum; however, the efforts have demonstrated the utility of such a study in optimizing the layout of critical structures related to dredging quantities. Also, this study avoided very expensive and possibly potentially adverse irreversible field construction work.

Murrell's Inlet, SC. Rosati and Kraus (1999) have reported on design and functioning of a deposition basin at Murrell's Inlet, SC. A dual jetty system was constructed in 1977 with a 400-

m-long weir section close to the shore on the north jetty. The crest elevation of the weir was 0.4 m above mean low water (mlw) and a deposition basin was dredged at 6 m below mlw on the lee side of southerly littoral drift. The navigation channel was at 3 m below mlw. Results of a 9-year monitoring program indicated that the sediment tended to transport over and through the weir jetty; however, some of it then bypassed the deposition basin and deposited in the navigation channel. It is likely that a sediment deflector wall (which was recommended, but not constructed) would have retained sediment within the deposition basin.

Ocean City Inlet, MD. Permeable jetties, and jetties with crest elevations that are low relative to the adjacent beach, can contribute to erosion of the adjacent beach and shoaling of the inlet channel. Rosati and Kraus (1999) have reported on the functioning of Ocean City Inlet, SC, as an example where modifications were made to the south jetty because water and sand were flowing over and through the jetty. A new south jetty was constructed 10 m south of the existing jetty with a crest elevation of 3.3 m (11 ft) relative to mean sea level (msl) instead of the earlier crest elevation of 1.2 m (4 ft) (msl). An impermeable core was provided, and three headland breakwaters were constructed. Results of a monitoring program indicated that the rehabilitation effort successfully met its goal of eliminating the shoaling problem.

Antwerp Harbor, Belgium. Pettweis and Sas (1999) conducted numerical model studies on sedimentation of mud in the access channels to the harbor at Antwerp, Belgium. They identified three major processes of mud siltation in these navigation channels, namely density flow, eddy formation in the dock, and tidal filling. It was concluded that a silt screen was not applicable for the site because of possible frequent damage by ships. The effect of a CDW, which is an obstruction to deviate the currents, is not well known when density-induced currents occur. Hofland et al. (2001) reported in a subsequent study that a CDW can be effective under density-induced currents; however, site-specific studies are essential.

Smits, Meyvis, and Wens (1994) have reported that busy navigation to and from the locks at Antwerp has resulted in the use of alternative dredging techniques such as the use of a sweep beam which reduces interruption to navigation that occurs with normal dredging operations. The sweep beam is a sort of bulldozer blade which pushes the settled mud back into the river for further natural transport away from the reach of interest. Since dredging occurs almost continuously, the influence of dredging works on the turbidity in the river is limited.

Green Harbor, MA. Weishar and Aubrey (1988) concluded that the sediment transported from the ocean by the combination of wave refraction, reflection, and propagation processes is primarily responsible for shoaling at Green Harbor, MA. The following recommendations were made to reduce shoaling:

- Reduce the fillet of sand on the lee side of west jetty.
- Raise the crest elevation of the east jetty and tighten the jetty to minimize wave overtopping during storms.
- Eliminate or reduce the length differential between the east and west jetties. This will reduce wave reflection.
- Provide bank protection to reduce erosion.

- Implement a beach grass plantation program augmented with sand fencing to minimize aeolian sand transport.

Pilot Channel Concept. The pilot channel concept consists of excavating a pilot channel of smaller cross section than the desired section and allowing the natural erosive action of the river to erode the pilot channel to its ultimate section. The major advantage of this method of channel realignment is that the cost of channel excavation is greatly reduced. However, it is essential to have sufficient time to allow the pilot channel to fully develop.

Pilot channels were first used in the United States on the lower Mississippi River during the 1930s. During that time, the Mississippi River was shortened by some 240 km (150 miles) for flood-control purposes. This work began after the devastating flood of 1927. Pilot channels were also used successfully on the Arkansas and Red Rivers. The field experience gained from the construction of a pilot channel is valuable for effecting channel realignment over long reaches of the river and also for bank stabilization, thus avoiding sediment deposition in navigation channels.

Red River Waterway, LA. The soil through which the Red River, LA, traverses is easily erodible. Also, the Red River is a high-energy river with channel velocities approaching 1.8 m (6 ft)/sec at average flow, and up to 3.6 m (12 ft)/sec during floods. This combination of easily erodible soils and high channel velocities resulted in the pilot channels started on the Red River developing quickly, usually during the first or second high water seasons following construction. Pinkard (1995) has reported on the realignment works on the Red River. The river experienced active bank caving and contained bend ways that were too sharp for safe commercial navigation. Based on the successful applications of the pilot channel concept for the Arkansas and other rivers, the Corps suggested that realigning the channel throughout the project reach be done to eliminate both problems and also result in reduction in flood stages. The Red River Waterway project was completed with all the realignment work. It has been reported that no maintenance dredging is required to keep the realignments open since their completion in 1994.

Laboratory Study of Dikes. Hidayat et al. (2000) conducted laboratory experiments in a channel with cohesive sediment by using two types of submerged dikes perpendicular to the channel: (1) a simple dike (rectangular in cross section), and (2) a dike with a trapezoid cross section. The objective of dikes was to prevent fluid mud from entering the navigation channel. It was concluded from experiments that vortex movement around dikes was an important factor which influenced fluid mud flowing towards the navigation channel. It was also found that the capability to control fluid mud inflow to the channel depended on the type of submerged dike and fluid mud height. The simple rectangular form of submerged dike generated a stronger vortex than did the trapezoidal dike.

Laboratory Study of River Water Exchange. Van Schundel and Kranenburg (1998) conducted laboratory studies on turbulent exchange of river water containing suspended sediment and clear water from a harbor with an objective of devising modifications of the harbor entrance for reducing siltation. Slightly heated water was used for simulating the density difference. They found three methods that would be effective: (1) a sill in the entrance, (2) a dam narrowing the entrance, and (3) a permeable pile-groin placed upstream of the entrance.

Riverine Harbors. Shoaling in riverine harbors and navigation channels depends on their size, shape, location with respect to the river channel, and characteristics of stream and flow hydrographs. The design of harbor entrances and associated structures needs to take into account the movement of sediment in the stream, alignment and velocity of currents, river stage variations, and the effect of harbor entrances and structures on the currents sediment movement (Melton and Franco 1979). The problem of shoaling reduction is complicated due to the large number of variables.

Melton and Franco (1979) described physical model investigations conducted on a truncated, schematic, movable-bed model setup having a horizontal scale of 1:400 and a vertical scale of 1:100. The model bed material consisted of crushed coal with a mean grain diameter of 2.0 mm and specific gravity of 1.30. The model reproduced a schematic reach of a representative river with two alternate bends, a straight reach, and a straight reach that could be considered as somewhat typical of the meandering characteristics of alluvial streams. Several general conclusions drawn from this basic study include: (1) Shoaling in harbor entrances considerably depends on their locations with respect to the alignment of the stream channel. Harbor entrances located along the concave bank of a stream will tend to have less shoaling problems than the harbors located on the convex; (2) Shoaling at harbor entrances depends on the curvature of bend, width of stream channel between banks, river flow hydrographs, and location of entrance with respect to the bend; (3) Generally, shoaling in the harbor entrance located in a straight reach will tend to be more than in an entrance located on the concave side of a bend; and (4) Shoaling in the harbor entrance is also affected by the size of the opening in the bank. It increases with width of opening and tends to be less with the opening angled toward downstream.

Effective Dikes. Dikes are commonly used for river training, flow diversion, and shoaling reduction; however, their design requires use of physical or numerical modeling. A variety of dikes have been used on innumerable projects all over the world. They include kicker dikes, spur dikes, submerged wing dikes, curved longitudinal dikes, trail dikes, transverse dikes, L-head dikes, etc.

Flow over the top of an L-shaped dike would tend to produce scouring along the entrance side, which would remove any material that may have been deposited during lower flows. An L-head dike structure has been successful in eliminating most of the shoaling in the lower entrance to the Chain of Rocks Canal in the Mississippi River during flows that overtop the structure. Wing dikes have been successful in reducing the amount of shoaling and dredging frequency in lower approaches on the Arkansas River.

St. Louis Harbor, MO. St. Louis Harbor, MO, is located on the convex side of a long-radius bend of the Mississippi River, about 24.1 km (15 miles) below the mouth of the Missouri River. Heavy shoaling in the lower entrance to the Chain of Rocks took place. To minimize shoaling, a trail dike was constructed along the river side of the entrance. This dike has been effective in reducing or eliminating shoaling during periods when the dike is overtopped. However, considerable dredging is required during low river stages. A movable model was constructed to horizontal and vertical scales of 1:250 and 1:100, respectively. Crushed coal with a median size of 4 mm and specific gravity of 1.3 was used for molding the model bed. The model study concluded that placing dikes along the right bank just upstream of the entrance to the Chain of Rocks Canal will tend to increase depths along the river side of the trail dikes and reduce shoaling in the entrance to the canal (Franco 1972).

Redeye Crossing Reach, Mississippi River. Redeye Crossing is located on the lower Mississippi River above Head of Pass about 5 km (3 miles) downstream of the I-10 Interstate Highway bridge at Baton Rouge, LA. The existing conditions with a 13.7-m-deep channel require about 2.3 million m^3 (3 million cu yd) of dredging annually to maintain the 12-m- (40-ft) deep navigation channel. A 13.7-m- (45-ft-) deep channel proposed for the area would drastically increase the annual dredging requirements. Pokrefke et al. (1995) reported results of numerical and physical model studies which evaluated effectiveness of proposed spur dikes at Redeye Crossing in reducing maintenance dredging requirements.

Numerical model results indicated that a dike plan consisting of six dikes on the left-descending bank with crest elevations of 0.6, 0.6, 2.1, 2.1, 2.1, 2.1 m (2, 2, 7, 7, 7, 7 ft), respectively from upstream to downstream, was the most effective. It was concluded that this dike field would reduce channel shoaling by about 90% for the 43-year-average annual hydrograph and 50 to 60% for the 1990 hydrograph.

Results of physical movable bed model study were conducted on the same dike plan consisting of six dikes on the left descending bank. It was concluded that this would reduce channel shoaling by about 60% for the 43-year-average annual hydrograph and about 27% for the 1982-83 hydrograph. Both estimates are based on current judgment, namely that numerical model estimates are optimistic and physical model estimates are conservative.

Smithland Locks and Dam, Ohio River. Franco and Pokrefke (1983) reported on a physical model study conducted on shoaling at the entrance to the Smithland Locks and Dam, Ohio River. It was concluded that shoaling in the lower lock approach could be eliminated or considerably reduced with the use of two wing dikes located near the end of the riverside lock wall.

Bendway Weirs. A bendway weir is defined as a rock structure located in the navigation channel of a bend, ideally angled at 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. A bendway weir is level-crested at an elevation low enough to allow normal river traffic to pass over the weir unimpeded. The weir must be of adequate height and length to intercept a large enough percentage of flow at the river cross section where the weir is located to produce several hydraulic improvements. Derrick et al. (1994) described the design and development of bendway weirs for the Dogtooth Bend reach of Mississippi River which were found effective where many types of river training structures were not successful.

CONCLUSIONS. It is absolutely essential to determine the following before even considering an appropriate method for reducing siltation in harbors and navigation channels:

- source of sediment (suspended sediment, bed erosion, bank sloughing, adjacent land areas, sediment recirculation, aolian sediment transport, littoral drift, flood/ebb shoal, porous land reclamation, other structures)
- critical natural parameter involved (tidal current, ocean influx, river discharge, tributary inflow, density current, waves, vessel-induced waves and currents, fluid mud, eddies, flow stagnation, meandering river, geomorphology, land runoff, sea level rise, land upheaval, overbank flow, existing structures, episodic events such as earthquake and storm)
- type of sediment (cohesive, noncohesive, mixture, calcareous, biogenic, loam, peat)

- time scale of shoaling occurrence (perennial, periodic, sporadic)
- total volume of sediment (to select suitable dredging equipment, and to determine benefit/cost ratio for proposed measures)
- importance of the location (national defense, recreational, environmental, archeological, commercial)
- location of major problem (specific channel reach, berths, estuary mouth)
- best approach to investigate the problem (physical modeling, tracer study, numerical modeling, field data analysis, desktop study)
- success or failure of measures taken at other sites under similar situation of site condition and natural parameters.

Several methods are available for reducing shoaling in harbors and navigation channels. The best-suited option for a given project must be well studied in advance to ensure its efficient functioning for the intended purpose. Sometimes a combination of various methods may have to be used. A list of measures grouped under seven categories is.

1. Reduce sediment inflow from the source.
    - Reduce vessel-induced bank erosion by controlling vessel type, speed, and distance from bank.
    - Provide bank protection works (including vegetation) to prevent sediment from eroding and sloughing.
    - Provide armoring for the channel bed.
    - Install French drains to stabilize basin slopes.
    - Rehabilitate existing structures, for instance to reduce threshold flow.
2. Prevent sediment from entering.
    - Install entrance closure structure.
    - Divert high sediment concentration flows.
    - Reduce the cross-section of the entrance by reducing width or by providing a submerged sill with a well designed crest elevation and location when the ocean is the main source of sediment.
    - Install barrier curtains near the bottom to exclude a major portion of suspended sediment from entering.
    - Prevent sediment from passing over or through jetties at tidal inlets, unless the project is equipped with a sediment trap.
3. Catch sediment before it enters the sensitive area.
    - Excavate a sand or sediment trap (also called sedimentation basin or deposition basin) at the site of shoaling or upstream of the area of interest in the path of sediment inflow.
    - Riverine or estuarine dike fields can also serve as sediment traps.
    - Construct jetties at the mouth of tidal inlets.
    - Construct offshore breakwaters at the harbor entrance.
4. Divert sediment away from the area of interest.
    - Install hydraulic diversion dikes.
    - Install current/sediment deflector wall.
    - Install hydraulic jets to loosen local fresh sediment deposits for transport away by tidal currents.

- Install a vortex foil array to induce local scour and allow sediment to be carried away by tidal currents.
- Change flow patterns to alter sediment pathways.

5. Prevent sediment recirculation.
   - Use confined areas for sediment disposal.
   - Avoid placing dredged sediment close to the navigation channel. Select alternative sites for sediment placement.
   - Avoid agitation dredging, or at least ensure that resuspended sediments do not return to the problem areas.
   - Cap underwater disposal areas with nonerodible material to prevent their resuspension.
6. Prevent/induce sediment deposition.
   - Increase channel flow velocity to keep sediment in suspension and prevent its deposition.
   - Increase channel cross-section for inducing sediment deposition elsewhere, away from the reach of interest.
7. Other options.
   - Provide hydraulically optimized basin and/or channel geometry.
   - Reduce channel width/cross-section.
   - Realign navigation channel.
   - Provide half-tide harbor.
   - Select new site with more favorable conditions for locating expansion facilities.
   - Try in-the-field construction of a pilot channel, and monitor its behavior on flow and sedimentation pattern and velocity distribution. If the results are favorable, carry out channel realignment for sediment flushing, and to arrested bank erosion.
   - Perform advance maintenance dredging to avoid emergency dredging and to reduce frequency of dredging.
   - Freshwater inflows to estuaries can be manipulated to alter salinity gradients, thus influencing sediment deposition patterns.
   - Structures to alter wave penetration into harbors can alter sediment deposition patterns.

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